RECONSTRUCTION OF BUILDING FAÇADES USING SPACEBORNE MULTIVIEW TOMOSAR POINT CLOUDS

Muhammad Shahzad [(1)] *and Xiao Xiang Zhu* [(1, 2)]

(1) Department of Remote Sensing Technology (LMF), Technical University Munich, Arcisstrasse 21, 80333 Munich, Germany (muhammad.shahzad@bv.tum.de)

(2) Remote Sensing Technology Institute (IMF), German Aerospace Center (DLR), Oberpfaffenhofen, 82234 Wesseling, Germany (xiao.zhu@dlr.de)

ABSTRACT

In this paper we present an approach that allows automatic reconstruction of building façades from 4D point cloud generated from tomographic SAR processing. The approach is modular and works by extracting façade points from the point density projected onto the ground plane. Individual façades are segmented using an unsupervised clustering procedure. Surface (flat or curved) model parameters of the segmented building façades are further estimated and finally the geometric primitives such as intersection points of the adjacent façades are determined to complete the reconstruction process. The proposed approach is illustrated and validated by examples using TomoSAR point clouds generated from TerraSAR-X high resolution spotlight images.

Index Terms— SAR tomography, TerraSAR-X, façade reconstruction, point cloud, clustering

1. INTRODUCTION

Space-borne meter resolution SAR data, together with multi-pass InSAR techniques including persistent scatterer interferometry (PSI) and tomographic SAR inversion (TomoSAR), allow us to reconstruct the shape and undergoing motion of individual buildings and urban infrastructures [1]-[4]. TomoSAR in particular offer tremendous improvement in detailed reconstruction and monitoring of urban areas, especially man-made infrastructures [3]. The rich scatterer information retrieved from multiple incidence angles by TomoSAR in particular enables us to generate 4D point clouds of the illuminated area with a point density comparable to LiDAR. These point clouds can be potentially used for building façade reconstruction in urban environment from space with few considerations: 1) Side-looking SAR geometry enables TomoSAR point clouds to possess rich façade information; 2) Temporarily incoherent objects, e.g. trees, cannot be reconstructed from multi-pass space-borne SAR image stacks [8]; 3) The TomoSAR point clouds have a moderate 3D positioning accuracy in the order of 1m, while (airborne) LiDAR provides accuracy typically in the order of 0.1m.

Besides these special considerations, object reconstruction from these points can lead to the development of dynamic city models that incorporate temporal behavior along with the 3D information. This can potentially lead to monitor and visualize the dynamics of urban infrastructure in very high level of details. Motivated by the chances and needs, this paper attempts to detect and reconstruct the building façades from these TomoSAR point clouds generated from both ascending and descending orbits.

2. METHODOLOGY

The proposed approach consists of three main steps including façades (detection) extraction, segmentation and reconstruction. These individual modules are outlined next.

2.1. Façade points extraction

While developing the façade points extraction method, characteristics of TomoSAR point clouds introduced by the side-looking SAR geometry are taken into consideration. When projected onto ground plane, vertical façade regions exhibit much higher scatterer (point) density *SD*. It is mostly due to the existence of strong corner reflectors e.g., window frames on the building façades. This encouraged us to extract vertical façade points by locally estimating the scatterer density for each point and retaining only those points that have relatively higher *SD* value.

2.1.1. SD estimation

For each 3D TomoSAR point p, points within its local neighborhood v_c are used for *SD* estimation. v_c includes all those points that lie inside a vertical cylinder centered at p. However to incorporate façade geometry in estimating *SD*, covariance matrix Σ_{v_c} of points in v_c are computed. Distance to the principal axis i.e., eigenvector of the largest eigenvalue of Σ_{v_c} is then calculated for every point in v_c. The points having distances less than d are taken as “inliers” and are used in *SD* estimation.

SD for each point is thus defined as the number of points within a directional (cylindrical) neighborhood window divided by the area of that window:

$$SD = \frac{\sum_{p_i \in v_d} p_i}{A_{v_d}} \quad (1)$$

where $v_d \subseteq v_c$ but includes only those points that lie close to the principal axis of points in v_c.

Points having *SD* value less than a specified threshold *TH* are removed. Usually, remaining points not only include façade points but also other non-façade points having higher *SD* e.g., building roof points. These points must be removed prior to further processing.

2.1.2. Surface normals

To reject points having higher *SD* but not belonging to façades, surface normals are computed for each 3D point in their local neighborhood v_c using eigenvalue approach. Robust estimation of covariance matrix Σ_{v_c} for estimating plane coefficients $n_x x + n_y y + n_z z + \rho = 0$ is employed using minimum covariance determinant (MCD) method with h = 75% [5]. Surface normals for each 3D point is then taken as the eigenvector of the smallest eigenvalue of Σ_{v_c}.

$$\begin{gathered} \Sigma_{v_c} . \mathrm{v}_j = \lambda_j . \mathrm{v}_j, \quad j = 1,2,3 \text{ (descending order)} \\ \text{Surface normal: } N(n_x, n_y, n_z) = \mathrm{v}_3 \end{gathered} \quad (2)$$

Finally, façade points are extracted out by retaining only those points having normals close to the horizontal axis.

2.2. Segmentation of individual façades

To reconstruct individual façades, segmentation of the points belonging to the same façade is required. Most segmentation approaches make use of unsupervised clustering techniques. They typically search for local plane features and then perform neighborhood analysis using the detected features. Only considering the planar segments can be too restrictive as in appearance of the curved surfaces that can be better modeled using second or higher order polynomials. Therefore, we search for both planar and curved surfaces and further distinguish them by local footprint orientation analysis.

Extracted façade points are first coarsely clustered using density based clustering algorithm proposed by Ester et al. [6]. It involves the notion of density connectivity between the points. For example two points are directly density connected to each other if one is in the neighborhood vicinity of the other point. If the two points are not directly connected to each other, still they can be density connected to each other if there exists a chain of points between them such that they all are directly density connected to each other. Two parameters that control the clustering process include ε and MinPts. The former is the neighborhood parameter e.g., radius in case of sphere or cylindrical neighborhood while the later indicates the minimum number of points in the ε-neighborhood for any particular point. The resulting clusters K_i contains points such that all the points in any particular cluster are density connected to each other but are not density connected to any other point belonging to another cluster.

Clusters obtained after density based clustering need to be finely clustered. Clusters that group more than one façade are further clustered via meanshift clustering algorithm using their surface normals [7]. In this way, the points that belong to different façades having similar normals that are spatially closely spaced but not connected are still clustered into one group. Therefore, the density based clustering is again performed here to separate these clusters. Finally, clusters with very few points are removed from further processing for robust reconstruction.

2.3. Reconstruction

Façades consists of planes, intersection lines (ridges), edges (façade boundary) and the corresponding vertices. These features will be reconstructed in this section. Mostly, reconstruction approaches follow the strategy of fitting planes in the segmented points and use some distance metric to identify adjacent segments. Instead of fitting planes in the segmented points, we adopt a different strategy: the surfaces are first classified to flat or curve surfaces; the façade footprint is then estimated using the weighted least squares method.

2.3.1. Model identification & parameter estimation

The façade surfaces to be modeled are first classified to flat and curved surfaces by analyzing derivatives of the local orientation angle θ. θ for each 3D point is equal to the azimuthal angle of the corresponding computed surface normals:

$$\theta = \arctan\left(\frac{\lambda_{3y}}{\lambda_{3x}}\right) \quad (3)$$

where λ_{3x} and λ_{3y} represents the *x* and *y* components of the surface normal λ_3 of any 3D point. Ideally, the flat surfaces should have constant orientations, i.e., zero derivatives compared to the curved surfaces that have gradually changing orientations. We exploit this fact and compute the first derivative θ' of the orientation angle for each façade footprint. Since the original orientation derivatives θ' are usually noisy, polynomial fitting is applied for denoising. Decision whether an individual façade footprint is flat or curved is based on the behavior of θ'. Façade footprints with unchanged orientation are considered to be flat while façade footprints with gradually changing orientation are considered to be curved. Polynomials are used to model the façade footprints in the *x*-*y* plane:

$$y = \sum_{i=0}^{p} a_i x^i \quad (4)$$

Flat and curved surfaces are modeled using first (p = 1) and second (p = 2) order polynomial coefficients. Higher order polynomials can also be used to model more complex building structures. Finally, model parameters for each segmented façade are estimated. Each extracted façade point is assigned weight corresponding to its SD. 2D façade footprints are then reconstructed by WLS method.

2.3.2. Vertex points determination

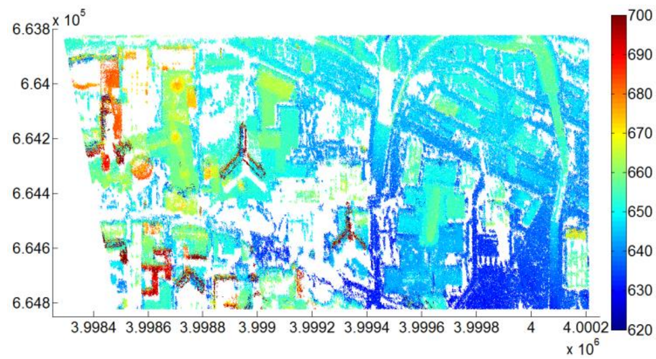
Once the façade model parameters are estimated, the final step is to describe the overall shape of the building footprint by further identifying adjacent façades pairs and determining the intersection of the façade surfaces. The adjacency of facades is usually described by an adjacency matrix that is built up via connectivity analysis. Identified adjacent façade segments are then used to determine the vertex points (i.e., façade intersection lines in 3D). They are found by computing the intersection points between any adjacent façade pair. Since polynomial models are used for façade parameter estimation, the problem of finding vertex points boils down to find the intersection point between the two polynomials corresponding to the two adjacent façades. The computed vertex points and the estimated model parameters are then used to finally reconstruct the 3D model of the buildings façades.

3. EXPERIMENTAL RESULTS

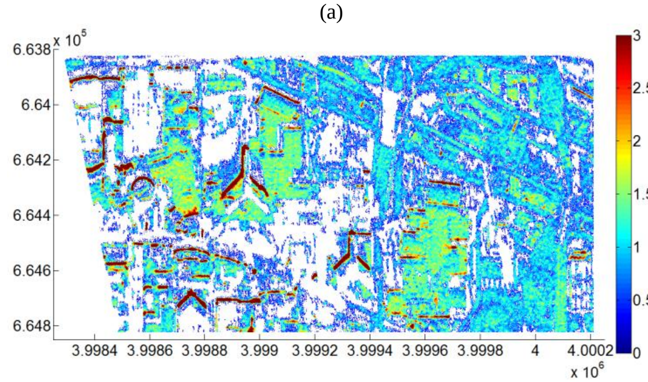
In order to validate our approach, we run the algorithm over TomoSAR point clouds generated from TerraSAR-X high spotlight images. Fig. 1(b) shows the result of applying *SD* estimation procedure. The two parameters *r* (radius of the neighborhood cylinder) and *d* are empirically set to 5m and 2m respectively according to the point density of the data set. One can observe that *TH* value influences the number of extracted façade points. Lower *TH* value results in higher completeness but lower correctness. To extract lower façades and to automate the procedure, the threshold *TH* is set to the maximum of *SD* histogram value. This includes not only the façade points but additionally also some nonfaçade points with relative high *SD*, e.g., roof points. To reject these points from the set of extracted points after *SD* thresholding, surface normals information is utilized. Fig. 1(c) shows the extracted façade points by retaining only those points having normals between ±15 degrees from the horizontal axis.

Extracted façade points from the previous step are further clustered into segments corresponding to individual façades. For this, we apply the clustering procedure using the cylindrical neighborhood definition and cluster all the points with parameter settings: $\varepsilon = r = 5$m and MinPts = 1. This result in clustering points that are density connected. In order to reconstruct individual façades, they need to be further clustered. To this end, mean shift clustering is applied, using Gaussian kernel with bandwidth parameter equal to 0.4, to the coarsely clustered segments in their normal feature space. Hereafter, we illustrate more detailed segmentation and reconstruction of individual buildings using examples of a smaller test area that includes two buildings (Bellagio Hotel, Las Vegas). Fig. 2(b) shows the estimated orientation angle θ for extracted façade points from single building shown in Fig. 2(a). The variation in orientation angle is quite evident and allows meanshift to cluster points having similar orientations together. This in turn requires further separation of points in the spatial domain. Density based clustering is again applied for separation and finally clusters with very few points (less than 50) are removed from further processing for robust reconstruction.

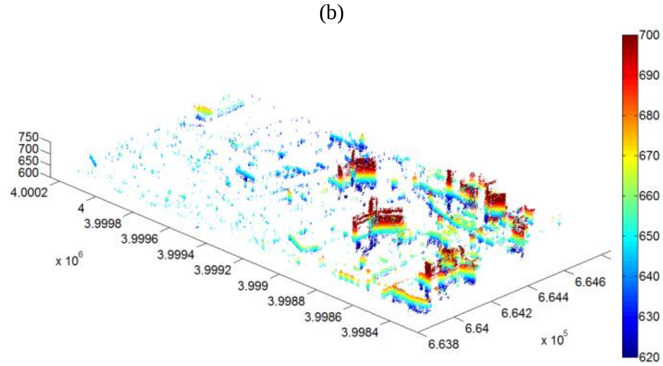
Prior to reconstruction, the segmented façades, are first classified to flat and curved surfaces by analyzing derivatives of the local orientation angle θ. Façade footprints with θ' estimates with slopes less than $0.01 \approx 0.6$ degrees) are considered to be flat. Fig. 3(a) depicts the reconstructed façade model in 3D model.



(a)



(b)



(c)

Fig. 1: Façade points extraction: (a) TomoSAR points in UTM coordinates (top view); (b) Scatterer (point) density with radius r = 2m and inliers d = 2m; (c) Extracted building façade points. Colobar indicates (a)(c) height in meters; (b) *SD*.

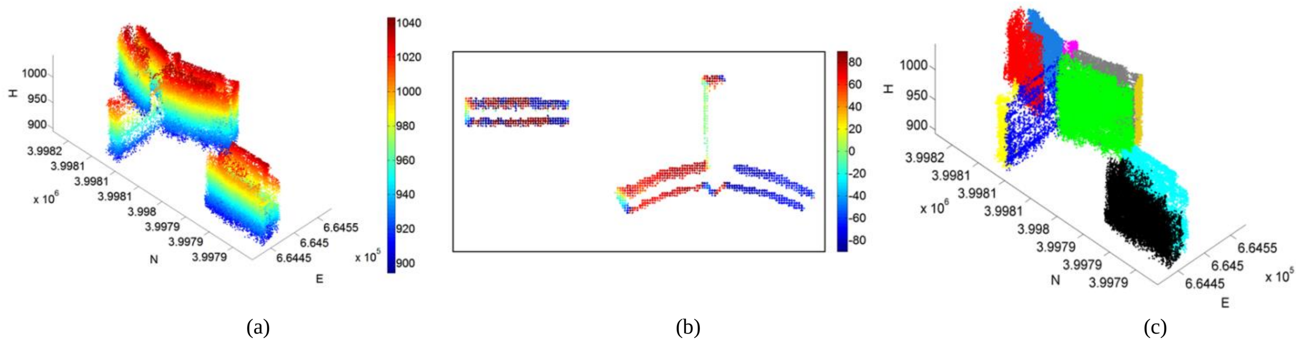


Fig. 2: Segmentation results of a single building: (a) Extracted façade points; (b) Orientation angle in degrees; (c) Clustered façade points.

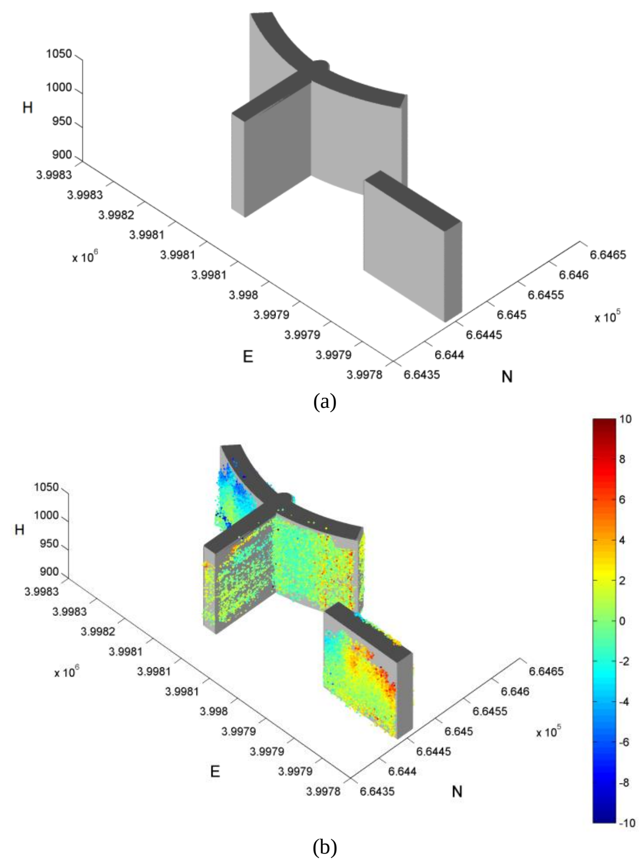


Fig. 3: Reconstructed building façade model: (a) 3D model; (b) 4D building façade model, amplitude of seasonal motion is color-coded. [unit: mm]

The reconstructed models can be used to refine the elevation estimates of the raw TomoSAR point clouds and reconstruct 4D building model [8]. An example of reconstructed spatio-temporal 4D model is presented in Fig. 3(b). TomoSAR points are visualized by overplotting them onto the reconstructed façade model. The colorcoded points represent the corresponding estimated motion parameter, i.e., the amplitude of seasonal motion caused by thermal dilation.

4. CONCLUSION

In this paper we have presented an automatic (parametric) approach for façade reconstruction using TomoSAR point clouds. It consists of three main steps: façade extraction, segmentation and reconstruction. In our experiments, we rely on the assumption of having a high number of scatterers on the building façades. In most cases, the assumption is valid because of the existence of strong corner reflectors, e.g. window frames, on the building façades. However there are exceptional cases: 1) The façade structure is smooth i.e., only very few scatterers can be detected on the façades; 2) The building is low. In these cases, *SD* might not be the optimum choice. Alternatively, we can use other scatterer characteristics such as intensity (brightness) and SNR for extraction and reconstruction purposes. In the future, we will also concentrate on object based TomoSAR point clouds fusion, building roof reconstruction and automatic object reconstruction for large areas.

5. REFERENCES

[1] R. Bamler, M. Eineder, N. Adam, S. Gernhardt and X. Zhu, "Interferometric Potential of High Resolution SpaceborneSAR", *Photogrammetrie – Fernerkundung – Geoinformation (PGF)*, pp. 407- 419, 2009.

[2] S. Gernhardt, N. Adam, M. Eineder and R. Bamler, "Potential of Very High Resolution SAR for Persistent Scatterer Interferometry in Urban Areas", *Annals of GIS*, 16 (2), pp. 103-111, 2010.

[3] X. Zhu and R. Bamler, "Very High Resolution Spaceborne SAR Tomography in Urban Environment", *IEEE Transactions on Geoscience and Remote Sensing*, 48(12), pp. 4296 – 4308, 2010.

[4] D. Reale, G. Fornaro, A. Pauciullo, X. Zhu and R. Bamler, "Tomographic Imaging and Monitoring of Buildings with Very High Resolution SAR Data", *IEEE GRSL*, 2011, 8 (4), pp. 661-665.

[5] M. Hubert, P. Rousseeuw, K. V. Branden, "Robpca: A new approach to robust principal components analysis", *Technometrics* 47, 2005.

[6] M. Ester et al.,"A density-based algorithm for discovering clusters in large spatial databases with noise", *KDD-1996*, AAAI Press. pp. 226–231. ISBN 1-57735-004-9.

[7] Y. Liu and Y. Xiong, "Automatic segmentation of unorganized noisy point clouds based on the gaussian map", *Computer-Aided Design*, 40(5):576–594, 2008.

[8] X. Zhu and M. Shahzad, "Façade Reconstruction Using Multi-View Spaceborne TomoSAR Point Clouds", *IEEE TGRS*, accepted subject to minor revision, 2013.